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EFFECT OF Al_2O_3 NANOPARTICLES ON THE PERFORMANCE OF PARAFFIN PHASE CHANGE MATERIAL THERMAL STORAGE SYSTEM

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ABSTRACT

The present study investigates the effect of nanoparticles on the performance of Paraffin wax in a latent heat thermal storage system. The experiments are conducted using organic compound which is paraffin wax with 0.5, 1 and 1.5% (volume) aluminium oxide (Al_2O_3) nanoparticles. Thermal storage system is designed and fabricated as per the design dimensions. The thermal storage system uses PCM which undergoes the phase change during the charging and discharging cycle. The heat input (Ein), heat absorbed (Eab) and temperature profiles for charging and discharging are evaluated for the nanoparticles when combined with Paraffin PCM materials. The study reveals that 1.5% Al_2O_3 with 2.5 kg of Paraffin wax blend results better performance characteristics. The heat transfer rate is 17% higher for Paraffin wax with 1.5% Al_2O_3 compared to neat paraffin wax operation. Hence, combination of the nanoparticles with PCM gives better thermal performance during charging and discharging conditions.

KEYWORDS: Paraffin Wax (PCM), Thermal Storage System, Nanoparticles & Thermal Conductivity

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Original Article

1. INTRODUCTION

The increased energy consumption of the world has resulted in energy crisis. The byproduct obtained during the conversion of fossil fuels into energy can cause climate change due to global warming. Recent studies predict that, in 2040, the world's primary energy requirement will increase by 48% [1]. Due to rapidexhaust of fossil fuel sources it is necessary to search for sustainable energy sources to meet this demand. There are various types of sustainable energy sources available and these sources are playing major role in balancing the consumer demand [2]. Sustainable energy sources are renewable in nature, but due to their unpredictability it is necessary to store these energy. Storage of renewable energy is a challenging task due to poor storage efficiency. Several research has been carried out all over the world to develop efficient and effective energy storing methods. These energy storing methods must be sustainable in nature in order to achieve long lasting operation. Depending on the type of energy sources, the energy storage systems are used. Solar energy can be adapted into electrical energy and stored in batteries whereas as thermal energy storage (TES) systems are used to store solar thermal energy. TES systems have several advantages such as higher overall efficiency and improved steadfastness, which leads to better economics, minimum investment and operating costs, and pollution free environment [3].

There are two types of thermal energy storage systems used viz. sensible heat storage system and latent heat storage system [4]. Sensible heat storage systems are used for low temperature storage and latent heat storage systems are used for high temperature storage applications. Sensible heat TES systems with molten salts are widely used in concentrated solar thermal power (CSP) plants and are commercialized. The major drawback of these TES

systems is lower operating temperature of molten salts and higher initial investments. Use of molten salts in TES requires more salts quantity and due to lower energy density it requires larger storage capacity of the system [5].

Latent heat TES systems, on the other hand, have higher efficiencies due to the use of phase change materials (PCM). The latent heat TES operates at higher temperatures and have higher energy densities. But, these systems are not yet used for large capacity CSP plants. Lower thermal conductivity of the phase change materials results lower charging and discharging rates [6]. This limits its use in large capacity TES systems.

Several researchers have tried to improve the efficiency of the TES system. Lee et al. [7] studied the charging and discharging characteristics of organic PCM materials. They used a mixture of paraffin wax and fatty acids and graphite nano sized particles as heat transfer improver. According to their report, the thermal conductivity of the mixture improved significantly and it was found to be 284% more than pure fatty acid and paraffin wax PCM mixture. Gasia et al. [8] developed TES system of commercial paraffin PCM by using industrial waste heat for water heating application. They studied the thermal behaviors such as energy rate, temperature variation during charging and discharging cycles.

Saw et al. [9] used paraffin wax with copper nanoparticles to form nano enhanced PCM and studied the temperature profiles of TES system. They used TES system for industrial hot water application. The TES system with nano-enhanced PCM showed better results compared to pure PCM TES system. Al-Jethelah et al. studied the melting characteristics of a latent heat TES system using coconut oil and CuO nanoparticles as nano-PCM. The TES with nano-PCM showed improvement in melting process compared to neat PCM. From the literature, it is clear that the use nano-sized metallic particles improve the thermal performance and enhance the heat transfer through the PCM. In the present study, an attempt has been made to investigate the effect of composition of Al_2O_3 nanoparticles on the temperature characteristics and heat transfer behavior of a TES system using Paraffin as phase change material.

2. MATERIALS AND METHODOLOGY

The experimental investigations have been conducted using a shell and tube type thermal energy storage system. The thermal storage system has been designed and fabricated as per the heat transfer principles. The following assumptions have been considered to arrive the solution:

- The heat exchanger tube is a straight tube of equivalent diameter running through the PCM.
- The thickness to PCM is uniform around the heat exchanger tube.
- Average value of PCM conductivity is assumed to be constant.
- The flow rate and temperature of the water is constant during charging the PCM so that the heat supply remains constant.

The following equation has been used to calculate the dimensions of the shell and tube for a given amount of PCM material.

Q = Sensible Heat of PCM (Heat of solid medium) + Latent heat of PCM + Sensible heat of PCM (Heat of liquid medium)

$$Q = \int_{T_1}^{T_m} mC_{ps}dT + ma_m\Delta h_m + \int_{T_m}^{T_f} mC_{pl}dT \quad (1)$$

Where, s

a_m is the melt fraction of PCM which is taken as 0.8

Δh_m is the latent heat of fusion, 173kJ/kg K.

Also,

Q= U. A. AMTD (2)

Where,

U= overall heat transfer coefficient, W/m^2K

$$U = {}^{1}\Big/_{1/h_i + 1/h_o\left(\frac{r_i}{r_0}\right)} \quad (3)$$

h_i, h_o : inner and outer convective heat transfer coefficients (W/m^2K)

A= Area, $2\pi rL$ (m^2)

AMTD= Arithmetic mean temperature difference

$$AMTD = \frac{T_{wi}+T_{wo}}{2} - \frac{t_{pi}+t_{pf}}{2} \quad (4)$$

Where,

T_{wi} = inlet temperature of water

T_{wo} = outlet temperature of water

T_{pi} = initial temperature of PCM

T_{pf} = final temperature of PCM

Following is the basic equation to calculate hi, i.e. in accordance with water that is flowing in the copper tube,

$$hi = N_U \times Kw/\, Di \quad (5)$$

Where,

Nusselt number N_U can be calculated by using the following empirical formula,

$$N_U = hiDi\, /\, kw \quad (6)$$

Kw is the thermal conductivity of water, W/ m K

Also,

$$N_U = 0.023 Re^{0.8} P_r^{0.3} \quad (7)$$

Where,

Re: Reynolds number

P_r: Pandtl number

P_r is given by,

$$P_r = \frac{\rho \vartheta C_p}{K} \tag{8}$$

Where,

ρ= Density of water, kg/m^3

ϑ= Kinematic viscosity, m^2/sec

C_p= Specific heat capacity, J/kg K

Kw= Thermal conductivity of water, W/m K

The velocity of water can be calculated by using Re,

$$Re = \frac{\rho V Di}{\mu} \tag{9}$$

Where,

Re= Reynolds number

ρ= density of water, kg/m^3

V= velocity of water, m/s

Di= inner diameter of copper tube, m

μ= dynamic viscosity of water, N s/ m^2

Following equation is used to calculate h_0, i.e. in accordance with Paraffin PCM outside the copper tube,

$$P_r = \frac{\rho \vartheta C_p}{K} \tag{10}$$

Where,

ρ= density of paraffin, kg/m^3

ϑ= kinematic viscosity of paraffin, m^2/sec

C_p= specific heat capacity of paraffin in liquid state, kJ/kg K

K= thermal conductivity of paraffin in liquid state, W/m K

$$Gr = \frac{D_0^3 \rho^2 g (T_{s,cy} - T_a) \beta}{\mu^2} \tag{11}$$

Where,

Gr= Grashof Number

D_o= outer diameter of copper tube, m

ρ = density of paraffin, 790 kg/m^3

μ = dynamic viscosity of paraffin, N s/m^2

g = acceleration due to gravity, m/s^2

β = coefficient of volume expansion of the paraffin

Ts,cy = cylinder's surface temperature, ^{0}C

Ta= ambient air temperature, ^{0}C

Length of copper tube can be determined by usingA= 2πrL, m

Volume of shell:

$$\rho = \frac{m}{V_{GI}} \tag{12}$$

Total volume to be covered by the GI shell:

$$V_{total} = V_t = V_{GI} + V_{Cu} \tag{13}$$

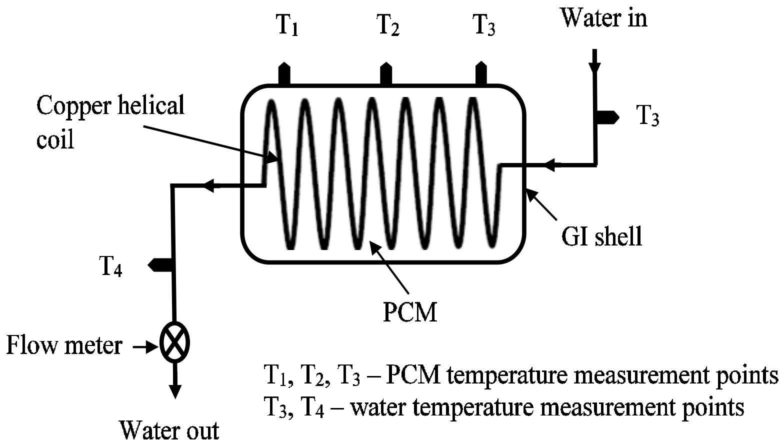

Figure 1: Schematic Representation of TES Setup.

The experimental TES as shown in the Figure 1 consists of a GI shell, inside which the copper coil is placed. In order to prevent leakage of PCM, the two ends of the shell are completely closed. The shell is properly insulated using glass wool to prevent heat loss. It has five temperature terminals to measure the temperature of PCM and water. Flow meter is used to measure the flow rate of water during charging and discharging cycles. In the present study, two kg of Paraffin wax is used as PCM and Al_2O_3 nanoparticles of 30 nm size is mixed at 0.5, 1 and 1.5% volume concentration. The nanoparticles are added to molten Paraffin wax and mixed thoroughly to ensure uniform distribution. Then the PCM is filled in the GI shell. PCM charging is done by supplying hot water through the coiled tube. Thermometers are used to measure the temperature of PCM and, water at inlet and outlet points. The charging and discharging test are conducted for 200 minutes duration.

3. TES TEST SETUP COMPONENTS

3.1 Shell

Figure 2 depicts the shell of the TES test setup. The shell is designed and fabricated as per the calculated value. Two holes are made along the length of the shell to connect the cooper coil, which is carrying water. The shell is made up of galvanized iron (GI) to resist corrosion. The outer surface of the shell is covered with glass wool, which provides proper insulation to minimize heat loss to the surrounding.

Figure 2: GI Shell.

3.2 Copper Tube

Figure 3 depicts the arrangement of copper tube for the circulation of water. The diameter and length of the copper tube are selected as per the design calculation. Copper tube has been made into spiral/ helical form by heat treatment. The spiral tube is then kept inside the shell and properly welded to the shell holes as shown in Figure 4. Then, the end plates are welded to the shell to form leak proof container in order to prevent the leakage of PCM.

Figure 3: Spiral Copper Tube.

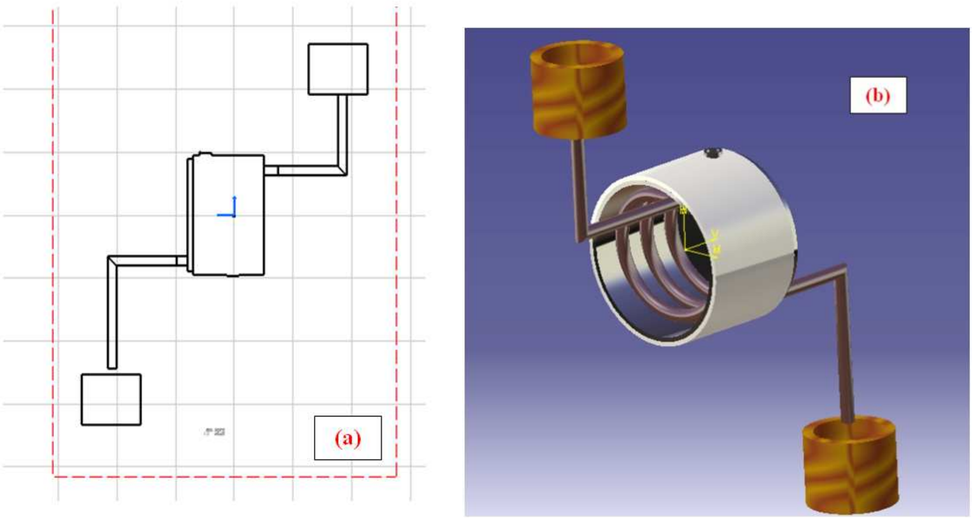

Figure 4: (a) 2D and (b) 3D Diagrams of the Experimental Setup.

4. RESULTS AND DISCUSSIONS

The tests are conducted at two different cycles namely, charging and discharging cycle. The heat input (*Ein*), heat absorbed (*Eab*) and temperature profiles for charging and discharging are evaluated for the nanoparticles when combined with Paraffin PCM materials**.**

4.1 Heat Transfer during Charging and Discharging

Figure 5 shows the variation of heat transfer to the PCM with time during charging. The amount of heat absorbed by the PCM increases as the concentration of Al_2O_3 nanoparticles increased. The heat transfer increases as the nanoparticle composition increased. Generally, PCM materials have poor thermal conductivity, and this results lower heat transfer through the PCM. Al_2O_3 nanoparticles are having higher thermal conductivity than paraffin wax. When metallic nanoparticles added to PCM, the thermal conductivity increases and the heat will be absorbed quickly. From the figure, it is clear that PCM with 1.5% Al_2O_3 nanoparticles exhibits maximum heat transfer and it is 17% more compared to neat Paraffin PCM. Figure 6 shows the variation of heat transfer to the PCM with time during discharging. Similar to charging, discharging process also shows similar result. Maximum heat transfer is achieved for 1.5% Al_2O_3 nanoparticles added PCM and is 56% more than neat paraffin PCM.

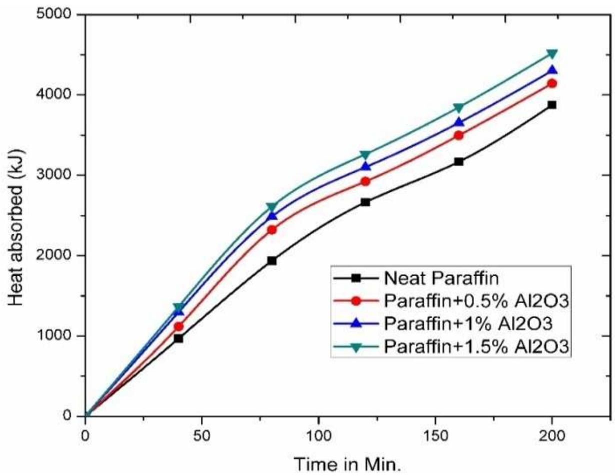

Figure 5: Heat Transfer during Charging.

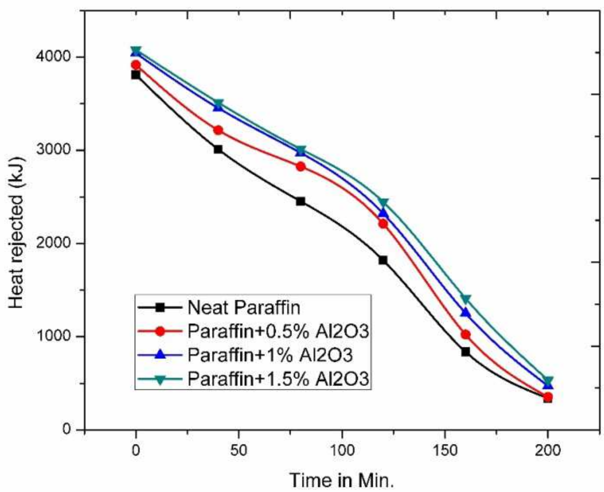

Figure 6: Heat Transfer during Discharging.

4.2 Temperature Profiles during Charging and Discharging

Figure 7 illustrates the variation of temperature for different PCM combinations with time for charging condition. PCM temperature increases with time; neat paraffin wax requires more to undergo phase change due to lower heat transfer. This is clear from the temperature profile of PCM materials. Due to the presence of nanoparticles, the temperature of PCM reaches higher value compared to neat PCM. To reach 52 °C, PCM with 1.5% Al_2O_3 nanoparticles require 135 minutes whereas neat PCM requires 200 minutes. Figure 8 shows the variation temperature during discharging condition. During discharging, the temperature of nanoparticles added PCM cools rapidly compared to neat PCM. This may be due to the rapid heat transfer to the water flowing through the copper tube. The presence of nanoparticle in PCM increases the thermal conductivity and hence the PCM temperature drops, results more hot water than neat PCM operation. In discharging operation, PCM with 1.5% Al_2O_3 nanoparticles shows lowest temperature compared to other PCM combinations.

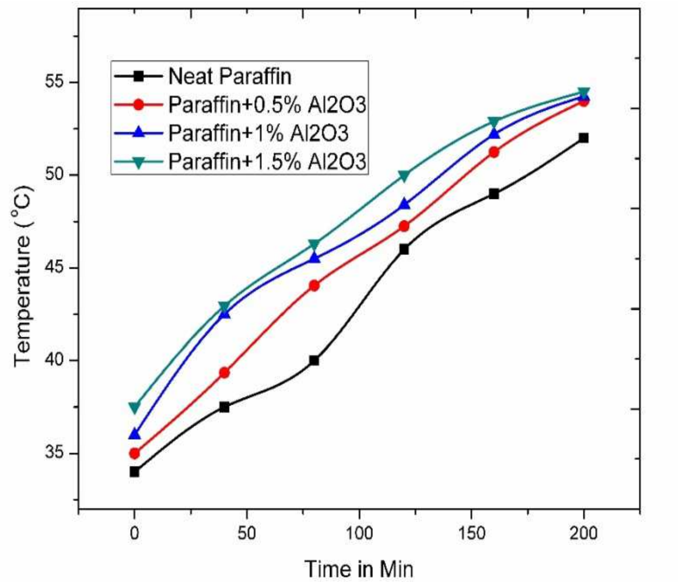

Figure 7: Temperature Rise during Charging.

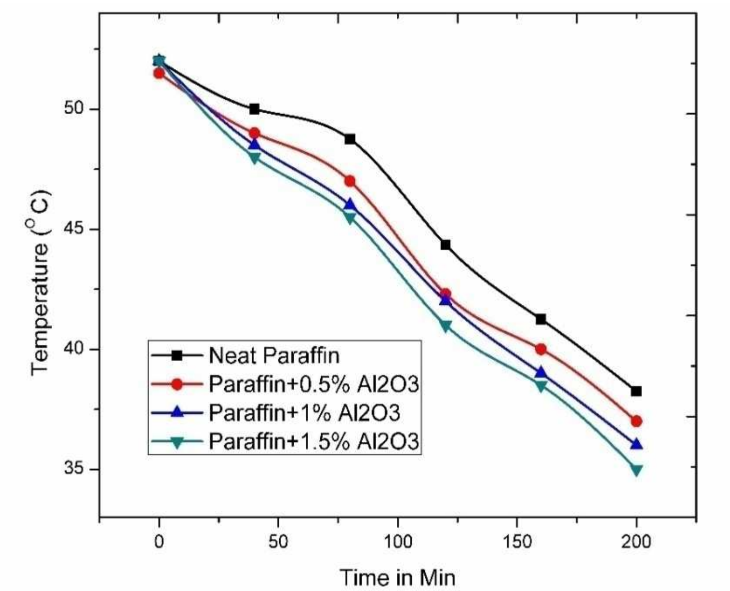

Figure 8: Temperature Drop during Charging.

5. CONCLUSIONS

In the present study, the effect of Al_2O_3 nanoparticles on the TES performance using Paraffin PCM has been investigated. From the findings following conclusions can be stated:

- Presence of metallic nanoparticle improves the heat transfer characteristics of the TES during charging and discharging operation.
- PCM with 1.5% Al_2O_3 nanoparticles shows better heat transfer characteristics during charging and discharging operation.
- When compared to neat Paraffin PCM, PCM with 1.5% Al_2O_3 nanoparticles exhibits –more heat transfer during charging operation.
- The temperature variation also approves superiority for nanoparticles added Paraffin PCM and maximum temperature value observed for 1.5% Al_2O_3 nanoparticles composition.

Hence, use of Al_2O_3 nanoparticles helps to improve the overall thermal performance of the TES system. The researchers have to focus on this area, for further research to implement this concept in large capacity commercial TES applications.

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